

Numerical Weather Prediction

**Forecast Error Investigation 12th October 2003:
Assimilation of Contaminated Wind Profiler Data into the Global Model.**



Forecasting Research Technical Report No. 465

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Forecasting Research Technical Report No. 465

Forecast Error Investigation 06z 12th October 2003: Assimilation of Contaminated Wind Profiler Data into the Global Model.

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Abstract.

Global Model forecasts are routinely monitored so that significant forecast errors may be identified and investigated. The objective is to identify deficiencies in the model so as to eliminate them from the model system and so as to guide priorities for future NWP research.

This report documents an investigation into a poor short-period forecast that occurred over the Great Lakes on the 12th October 2003. Using Global Model reruns and new techniques developed in order to identify the time and location of the introduction of the error into the Global Model system, it is shown that American wind profiler data that had been contaminated by migrating birds was being routinely assimilated. This data was found to have quality control information applied at source, intended to be used to indicate when the data was likely to be contaminated, but that this information was not being used within the forecasting process. Modification of the observation processing to allow use of these quality control flags selectively removed the contaminated data from the Global Model assimilation, and produced an improved forecast for the run under investigation. Further reruns within the period of October 2003 showed consistently improved analyses when compared with surface observations, and little detrimental effect was observed to any analyses.

The use of the wind profiler quality control information is due to be incorporated into the operational Global Model in October 2005.

History

Version 1.0	"Forecast Error Investigation 12 th October 2003: Assimilation of Contaminated Wind Profiler Data into the Global Model"	19 th August 2005
Version 1.1	Revised following comments by David Richardson.	15 th September 2005

1 Introduction.

1.1 Occurrence and Magnitude of the Error

During intervention by Ops Centre at 12z 12th October 2003, it was noted that the T+6 Global Model background field from QU06 12th October exhibited large MSLP errors in excess of 4mb when verified against SYNOP observations across the central and eastern areas of the Great Lakes, USA. This was unusual not only because this was a relatively large short-period forecast error, but also in that it was of a relatively benign frontal trough within a data-dense region of many observation types.

Fig 1 shows the MSLP forecast error as verified against the model analysis at 12z over the United States. The error over the Great Lakes is observed to be ~2-4 times larger than any other within North America at this forecast range. Typical MSLP errors over Europe at this time were found to be ~+/-0.1hPa (not shown).

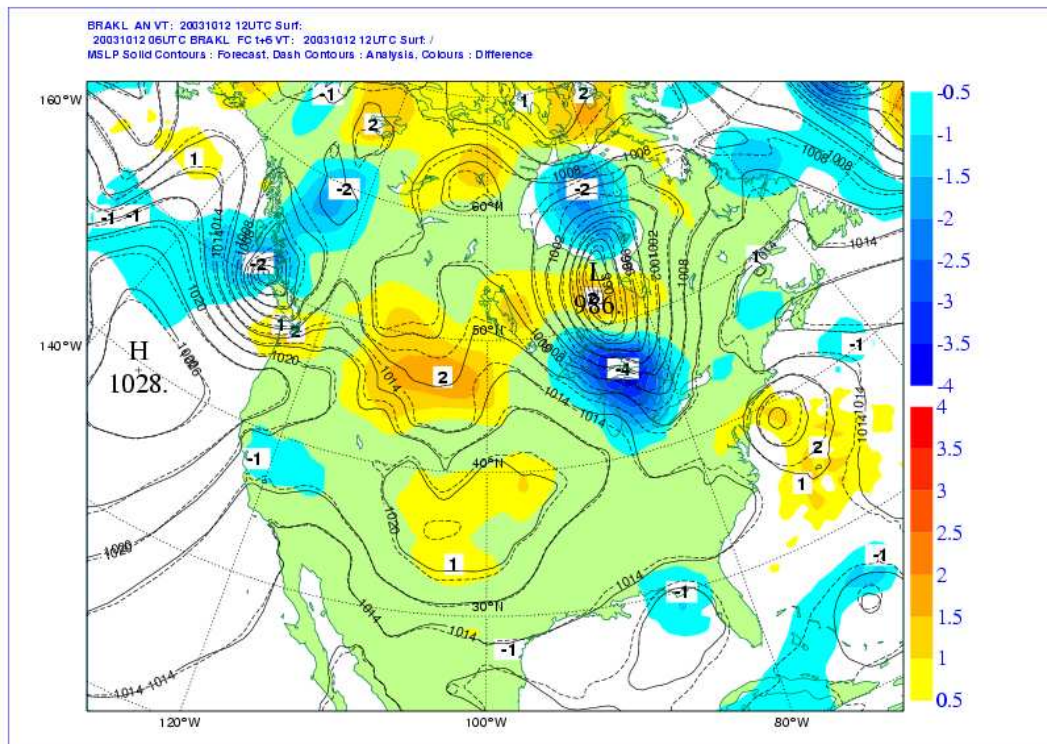


Figure 1 Global Model T+6 MSLP forecast error (colour), VT 12z 12th October 2003. The error over the Great Lakes is unusually large for a T+6 forecast over a region of dense observations. Also shown are the model analysis (solid) and background (dashed) fields.

Because of the relative magnitude of the short-period forecast error, this error may be indicative of a serious problem within the Global Model system (Model/Data Assimilation/Observations/OPS/Quality Control...) and the following investigation was carried out in order to identify its cause.

1.2 The Meteorological Situation

Fig 2 shows the meteorological situation at the time according to the Global Model analysis. During the morning of the 12th October, an upper trough was observed to swing NE through the Great Lakes driving a cold front ahead of it. A depression to the N extended S across the region, deepening by 5hPa in 12 hours. As the trough pushed away NE, pressure built in the area as an upper ridge, with associated surface anticyclone, moved in from the W.

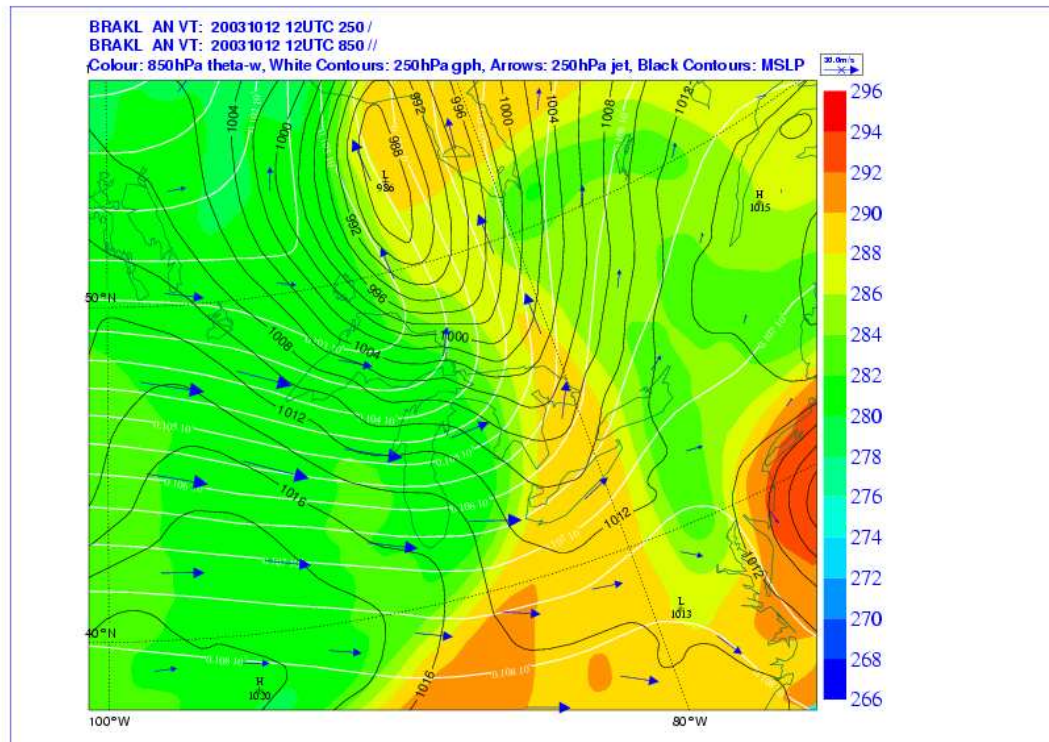


Figure 2 Global Model analysis for 12z 12th October 2003. Colour: 850hPa theta-w, black contours: MSLP, white contours: 250hPa gph, arrows: 250hPa wind vectors.

2 Verification Against Observations

Although a comparison of forecast with model analysis (Fig 1) clearly shows a forecast error of significant magnitude has occurred, it is instructive to directly verify the forecast against observations in the area. This provides a good indication of (i) how the data assimilation has responded to the observational data provided to it at a verifiable location, and (ii) provides an indication of the reliability of the observations that are being used as both assimilated data and as verification of the forecast.

Fig 3 shows a timeseries of observed (blue circle), background (green triangle) and analysed (red triangle) surface pressure P^* for land station 72645 in the Great Lakes region (44.5N 88.1W). Fig 4 shows the calculated

observation – background (O-B) residual values at the station over an 8-day period.

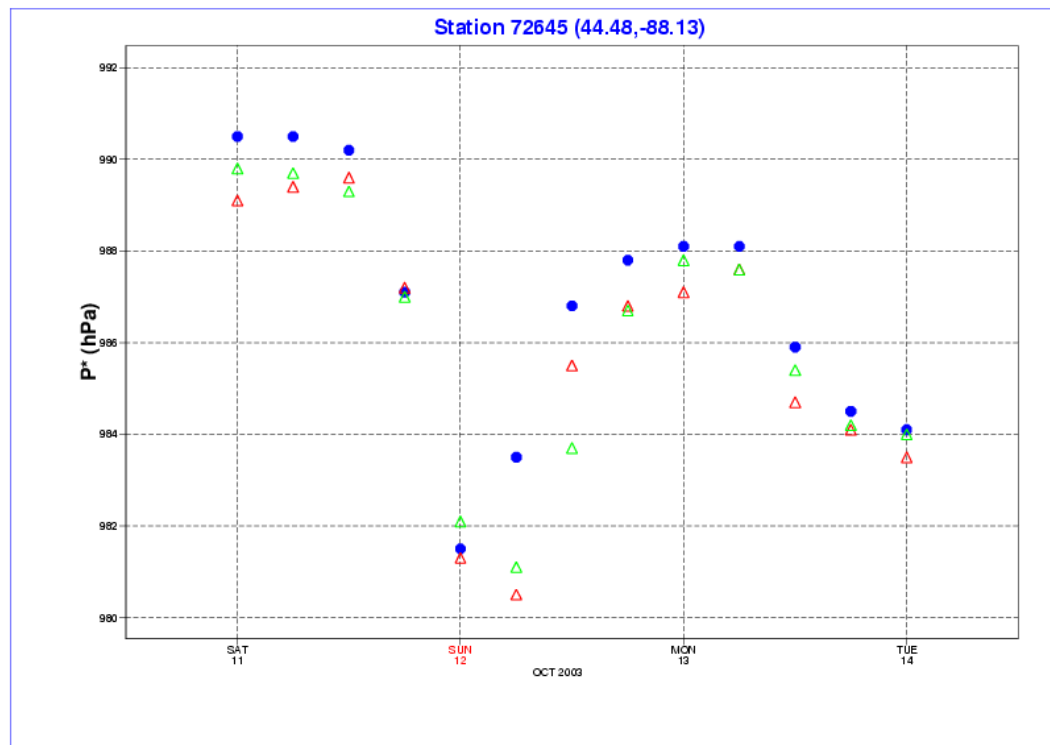


Figure 3 Timeseries of observed P* (blue circles), background P* (green triangles) and analysed P* (red triangles). The frontal trough passes through the station during the 11th and 12th October.

During the early part of the 11th October, the observed P* pressure is approximately steady, with the observed, background and analysis values agreeing well to within 1-1.5hPa. The O-B distribution of Fig 4 shows this has been the case for some days and that the observations from the station are of good quality, although the station suffers from a +1hPa bias from the background. During the latter part of the 11th and the early part of the 12th, the observed P* in Fig 3 is observed to fall sharply and then rise again later in the day. This period corresponds to the passage of the frontal trough across the station as discussed section 1. Fig 4 shows that during this time the maximum departure of the observation from the background is ~3hPa, indicating clearly the lack of consensus between the observed and model values.

The poor T+6 forecast verifying at 12z on the 12th may therefore be identified with the large difference between background (green triangle) and observation (blue circle) in Fig 3 and the large O-B departure of Fig 4. Fig 3 shows that the data analysis at this time (12z) has been largely successful with a model P* analysis value (red triangle) that is significantly closer to the observation than to the background. This T+6 forecast was generated from an (update) analysis created at 06z, and at this time it may be seen that for

this station the difference between the observation and the analysis is larger than that of the difference between the observation and the background.

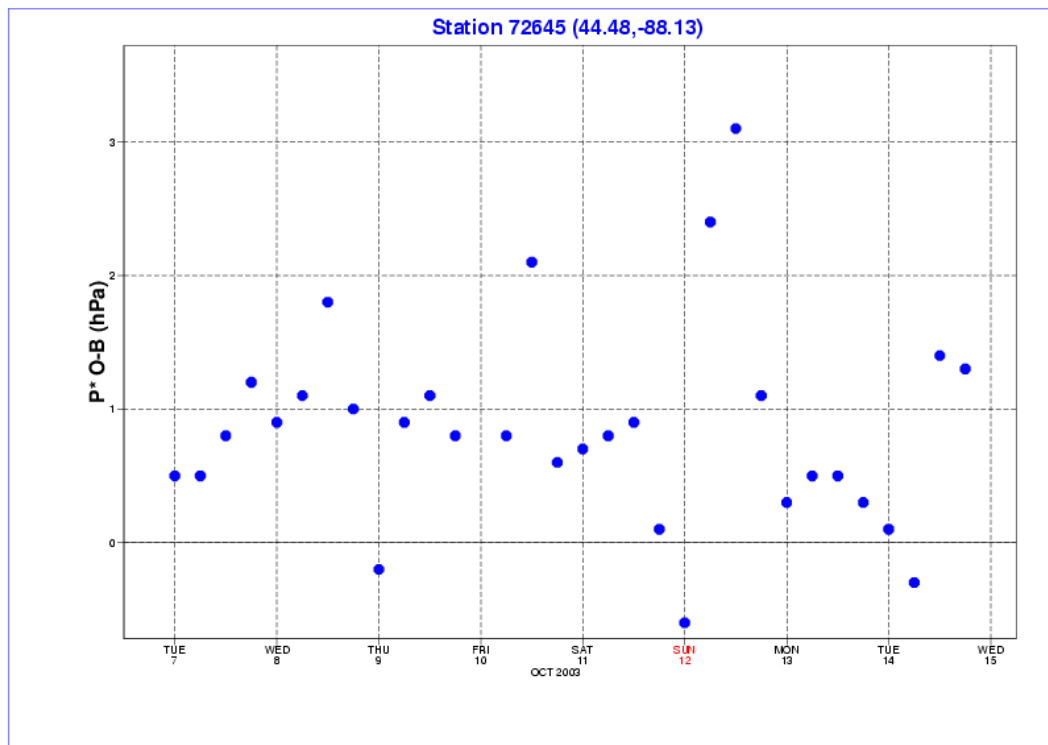


Figure 4 Timeseries of calculated Observation – Background P*. These are calculated after any bias correction is performed in the observation processing. This station shows a 1hPa bias relative to the background.

This timeseries analysis was repeated for a significant number of stations in the area (land and ship observations), all of which show the same signature of a large observation and background departure at 12z 12th. Further, the timeseries have shown that the quality of the data in the area is generally very good with little in the way of erratic behaviour. It may therefore be concluded that the analysis generated at 06z was of poor quality and that this resulted in a poor T+6 forecast that verified poorly at 12z.

3 Geographical Observation Departures & MSLP Analysis Increments

Given that the observations in the area are not in error and that the observed error is due to a poor background field, a method was created in order to further diagnose the effect of the data assimilation (3DVAR at the time of the case) with respect to the observations; the aim being to observe how the consensus between observations and background and between the observations and analysis varied geographically in response to the applied analysis increments. This is powerful information because the method identifies the location of any assimilation error.

The data assimilation creates the analysis by addition of positive or negative increments to the background field. If the data assimilation has been successful, then the departure of the observation from the analysis should be less than the departure of the observation from the background (hereafter termed the *analysis departure* and *background departure* respectively), and the analysis increments in that area are deemed correct. If the converse is true - and the analysis departure is greater than the background departure - then this identifies analysis increments that are judged incorrect.

The top half of Fig 5 shows the *geographical background departure diagram* for the operational QU06 12th October run. The top part of the figure shows the model MSLP background and analysis fields (dashed and solid lines) with the analysis increments (colour) and the departures of the observations from the background field at the station locations (triangles). The departures are colour coded so that the increasing O-B difference changes the station triangle from white through cream, green, yellow and red. The triangles are also upward or downward facing depending on if the O-B is positive (i.e. the background pressure is lower than the observed pressure) or negative (i.e. the background pressure is higher than the observed pressure) respectively. The figure shows that most station observations are ~0-1hPa or 1-2hPa above the background field (as indicated by the upward facing arrow), and therefore shows a good quality background field which is slightly too low with respect to surface observations.

To correct this small background departure one would expect a correct assimilation to produce either neutral or slightly positive analysis increments in the area, thus raising the model pressure in this area and offsetting the small positive O-B background departures. The assimilation would then produce an analysis that was closer to the observations than to the background and would represent a successful assimilation with respect to the surface observations. However the figure shows that negative MSLP analysis increments of ~1.8hPa were produced across a large area to the south of the Great Lakes. The effect of these increments on the resulting analysis may be identified by the lower part of Fig 5 which shows the *geographical analysis departure diagram*. This lower plot repeats the model fields and analysis increments of the top half, but this time displays the *analysis departure* values at each station location. In this diagram, many of the stations with small O-B values in the top diagram have become stations with larger O-A values in the lower diagram; these O-A departures are a direct result of the negative analysis increments in the area, and is a strong indication that the analysis increments in this location are incorrect. This implies, given correct observations (which have been verified as correct by the timeseries discussed earlier), that the analysis values at a large number of the station locations to the south and south-west of the Great Lakes are too low.

When this same analysis is applied to the QU12 run (Fig 6) the response of the data assimilation system to the situation is much better. The analysis increments produced are now positive and ~4hPa; this is the same order of magnitude but opposite in sign to the error shown in Fig 1 and represents the assimilation filling the under-deepened area over the Great Lakes.

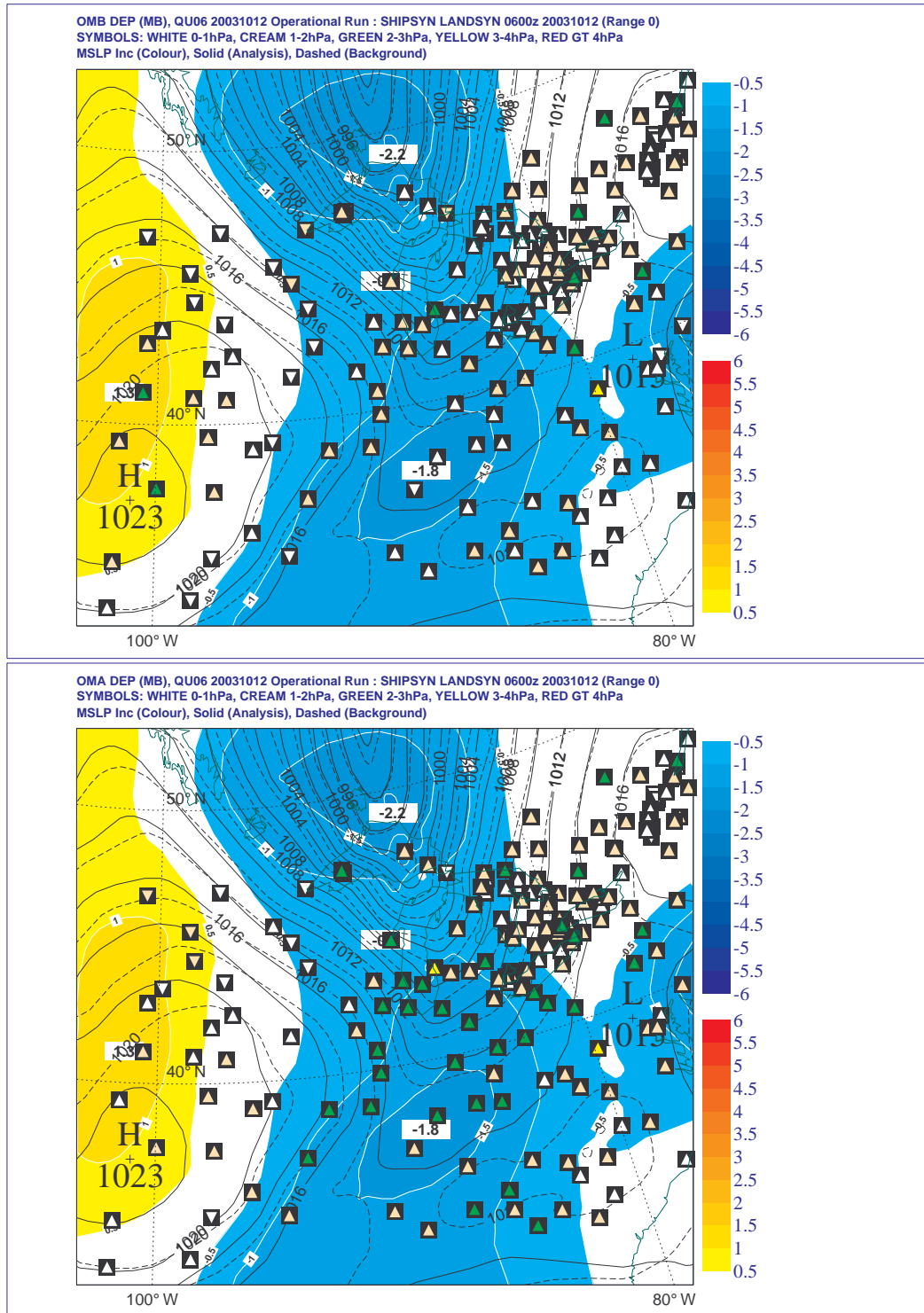


Figure 5 MSLP departures compared with MSLP analysis increments and MSLP background and analysis fields for the QU06 12th October run. Triangles show departures from (top) the background and (bottom) the analysis, with colour coding to represent the magnitude. The sign of the departure is represented by an upward or downward facing arrow depending on if the departure is positive or negative.

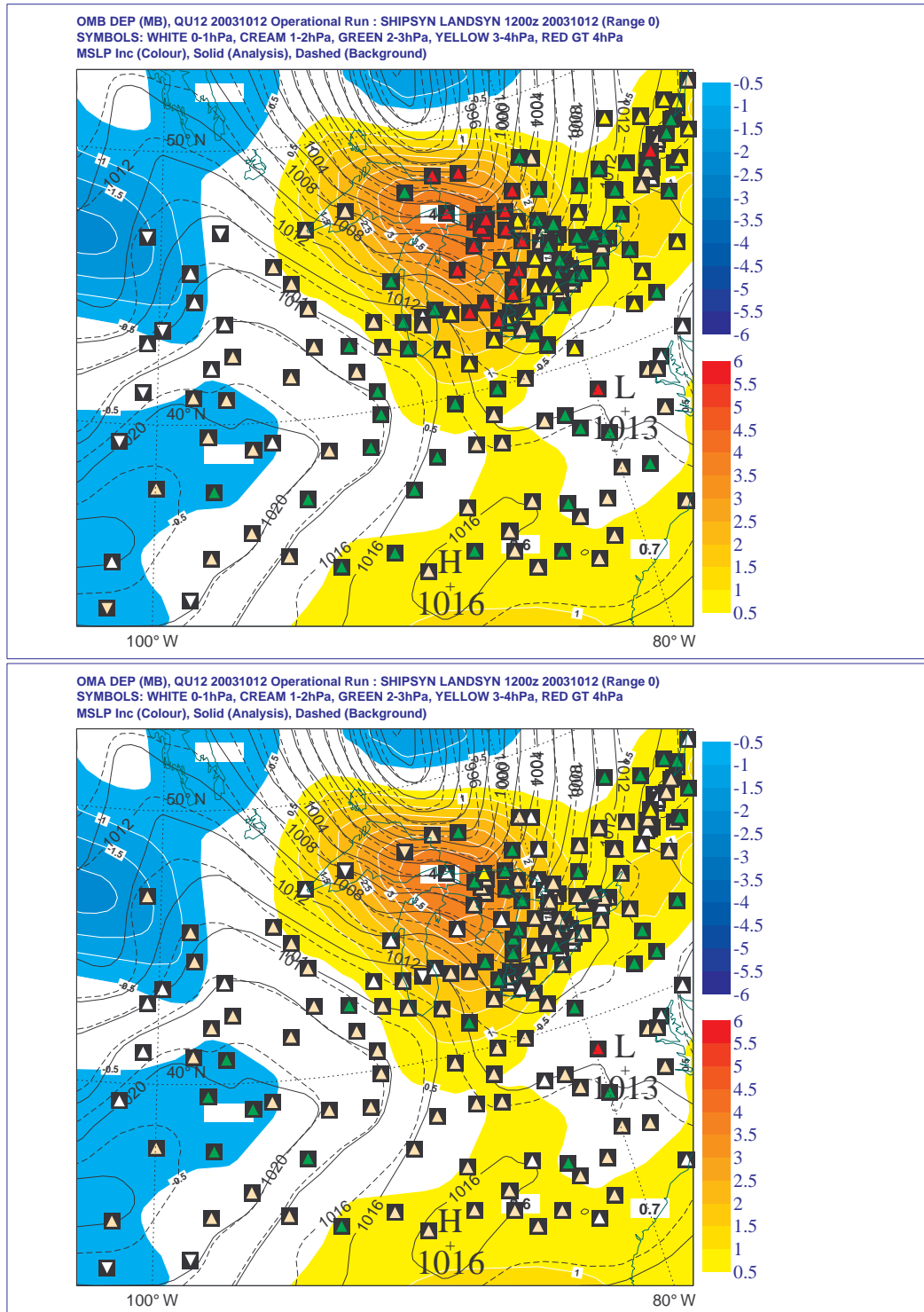


Figure 6 As figure 5 but for QU12 12th October,

The background departures (top figure) of the stations over the Great Lakes are large and positive (>4hPa) and show the original error that was identified by Ops Centre. The analysis departures (lower figure) are significantly reduced as a result of the increments showing that these increments verify well with respect to the surface observations.

This method therefore provides strong evidence to suggest further investigation into the observations which resulted in the negative MSLP analysis increments to the S and SW of the Great Lakes at 06z. This has directed the attention away from two other very plausible and large regions: (i) a short distance to the W or NW of the Great Lakes through the downstream propagation of an error or (ii) over the Great Lakes area itself, since the error may not have propagated very far within the time period of the short-period forecast.

4 Analysis Increment Contributions

4.1 *The Control Run.*

Given the strong evidence pointing to the negative MSLP analysis increments to the south of the Great Lakes, the next step in the case investigation involved the determination of the observation types that contributed to the analysis increments in this region. However, these analysis increments may not simply be the result of the poor assimilation of surface pressure observations because in producing an analysis it is necessary for the assimilation system to create a dynamically consistent set of increments from several observed parameters. From the point of view of error tracking, this complicates matters because it is not immediately clear what observations have resulted in the overall analysis increments.

In order to gain some understanding on the nature of the analysis increments and also to reproduce the model forecast error in a control experiment, a Global Model rerun for QU06 12th October was carried out. Analysis increments were then analysed in terms of key model/meteorological quantities that have been found to best understand the results of the data assimilation. These are MSLP, with wind, geopotential height, and temperature at 250, 500 and 850hPa. These analysis increments are shown in Figs 7-9, and are summarised thus:

- **Wind Increments:** Wind increments at upper and medium levels show modifications up to ~ 8m/s of the upper level jets. Increments of this order of magnitude relative to the full field are reasonable. At low levels there are very strong northerly increments ~12m/s and represent a significant modification to the background.
- **Geopotential Height:** Large negative gph increments have been created over the Great Lakes at upper levels that extend down to the surface. A large area of negative gph increments is also present from the mid to lower levels of the atmosphere to the S of the Great Lakes.
- **Temperature:** The area over the northern USA shows ~2C cooling with respect to the background field and results in a significant movement S/SE of the trailing surface front cold of the frontal trough.

- MSLP: These increments show a decrease $\sim 1.5\text{hPa}$ in MSLP across a very large area of the USA. They result in both a southerly extension of the surface trough situated across the Great Lakes, and also a weakening of the anticyclone to the SW of the Great Lakes. These increments reproduce well those shown in Fig 5.

The combined effect of these analysis increments on the background field may be understood as they generate an analysis with the following characteristics: the strong northerly wind increments located around 40N 100W at 850hPa result in strong cold advection on the rearward flank of the frontal trough. This is associated with (1) an extension of the frontal trough S, (2) a withdrawal of the anticyclone W, thus lowering the geopotential height, (3) a shift of the trailing cold front S, lowering the temperature to the rear, and (4) a decrease in the MSLP across the area.

Figure 7 Analysis Increments for QU06 12th October Control Rerun: 850hPa winds, 850hPa geopotential height, 850hPa temperature and MSLP.

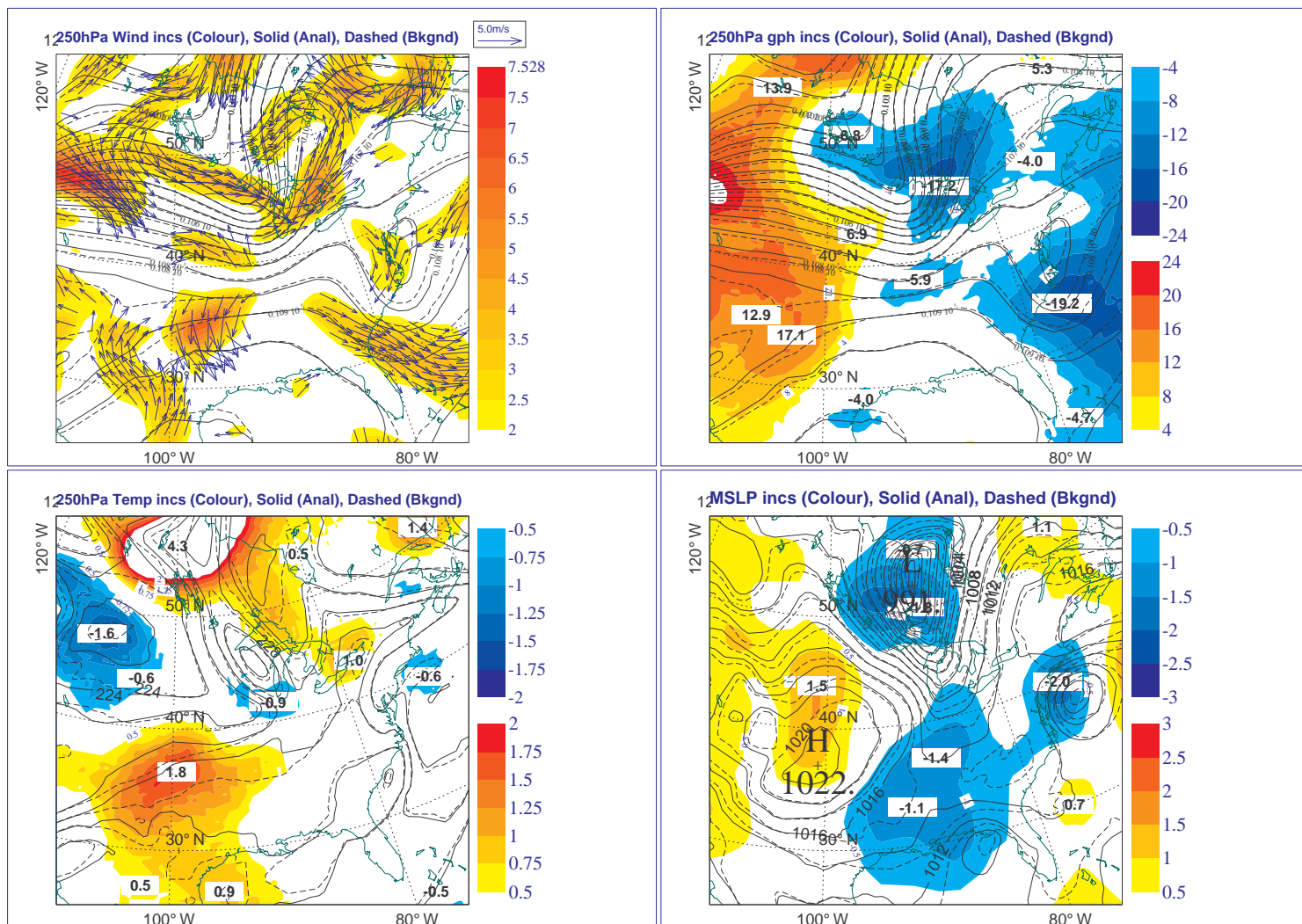


Figure 8 Analysis Increments for QJ06 12th October Control Rerun: 850hPa winds, 850hPa geopotential height, 850hPa temperature and MSLP.

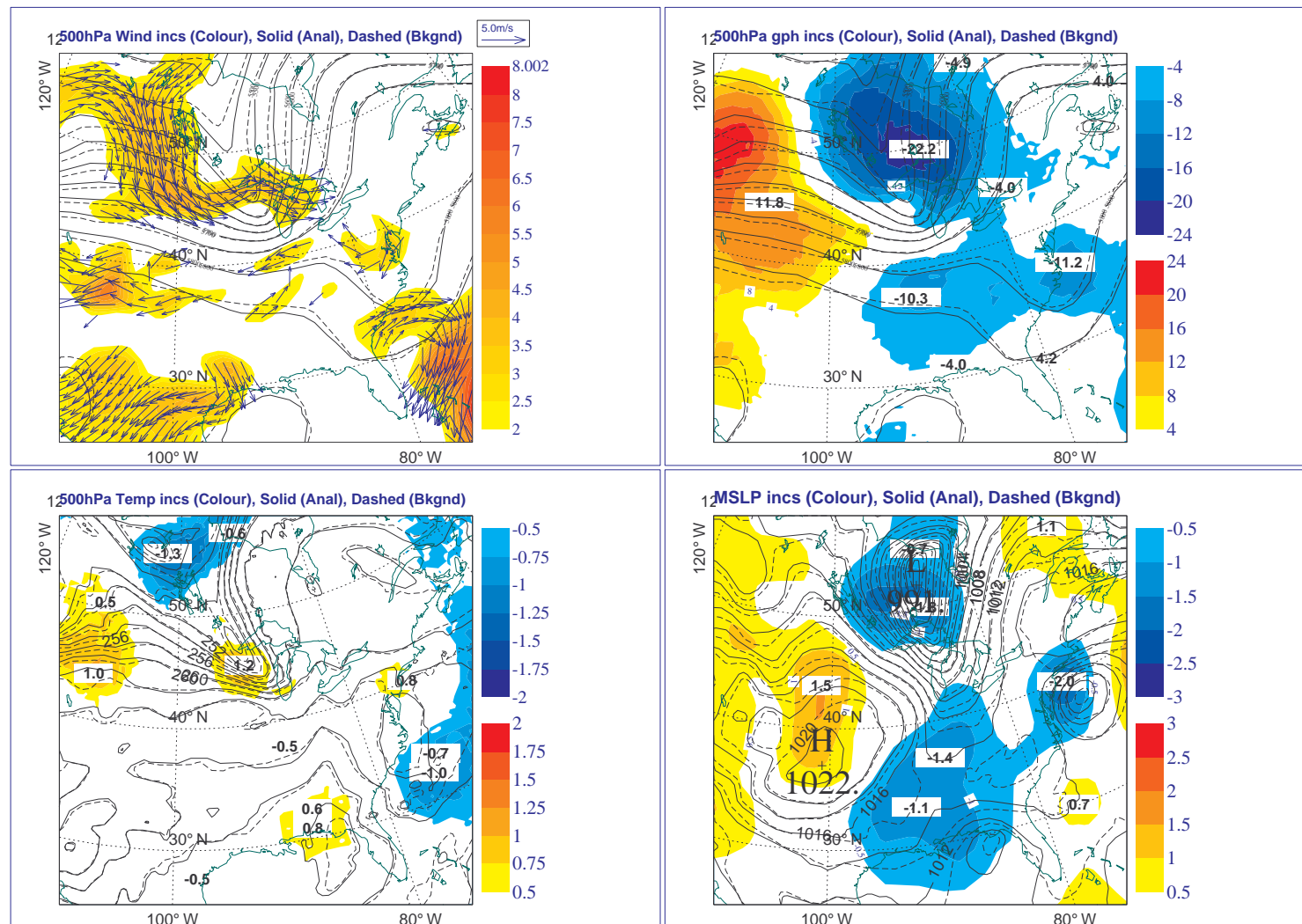
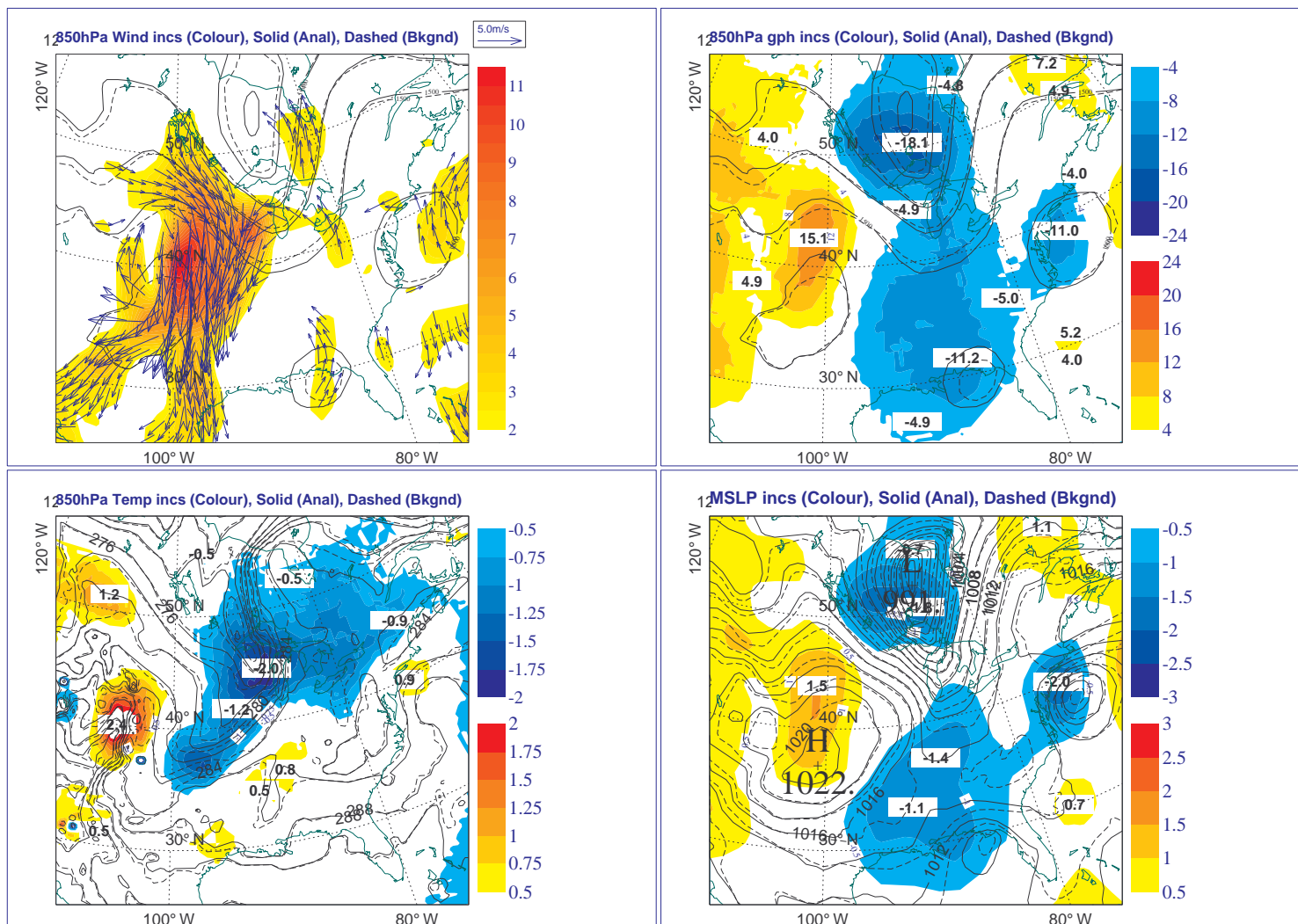


Figure 9 Analysis Increments for QU06 12th October Control Rerun: 850hPa winds, 850hPa geopotential height, 850hPa temperature and MSLP.



5 Single Observation-type Reruns.

It is clear that the observation type(s) causing the error must (1) be assimilated in the QU06 run, (2) contribute to ~2hPa negative MSLP analysis increments and (3) be over the central USA and to the south of the Great Lakes. Further, the strong northerly 850hPa wind increments to the SW of the Great Lakes are of particular interest because they represent a large area of significant modification to the background field and can only arise from a large departure of one or more observation types from the model background field in this region.

A number of reruns were therefore carried out in order to determine the contribution of each observation type to the identified analysis increments. In each rerun, only one observation type was assimilated – all others were specified as rejected in the station namelists provided as quality control specifications to the assimilation. The area in which to reject the observations being excluded from the run was determined by first performing a series of 'no-data' runs, the aim of which was to reduce the analysis increments across the area to the south of the Great Lakes to nil, thereby ensuring that single observation-type reruns to follow were uncontaminated by observations outside the exclusion area. This region, because of correlations within the background error covariance matrix, was found to be surprisingly large: 30-60N, 105-70W.

A series of model runs were then performed assimilating a single observation type. The observation-types assimilated in this area in the QU06 run were found to be Synops, Aircraft, ATOVS, Satwind and wind profiler data. The resulting MSLP analysis increments from each of the single observation-type runs are shown in Fig 10. Of these, the Synop, ATOVS and satellite winds all show either neutral or positive analysis increments, and are consistent with the earlier discussion in the requirement to create positive increments to offset the observed positive background departures. Aircraft data contributes some areas of negative increments but these are small (0.5-1hPa) and so would not result in -1.8hPa negative increments observed in the control run, especially when combined with the large positive increments obtained from the ATOVS and Synops.

In stark contrast, the wind profiler run shows negative increments of upto 6.9hPa across a very large area. These increments are very large – especially relative to the increments of the other re-runs, and strongly suggest that the wind profiler data are the primary cause of the poor analysis. The wind profiler contribution of large negative MSLP increments would easily, once incorporated with the smaller positive increments supplied by the other observation types, be enough to produce overall negative increments observed in the operational and control runs.

A re-run of all observation types with the exception of the wind profiler data was carried out in order to test the effect of the wind profiler data on the model

analysis. The resulting increments shown in Fig 10 show positive increments over much of the Great Lakes region, and therefore agree well with the deduced positive analysis increments in the earlier discussion. Further, the T+6 error is observed to reduce from ~4hPa to ~2hPa with a much improved fit to the observations as measured by the observation departures (not shown).

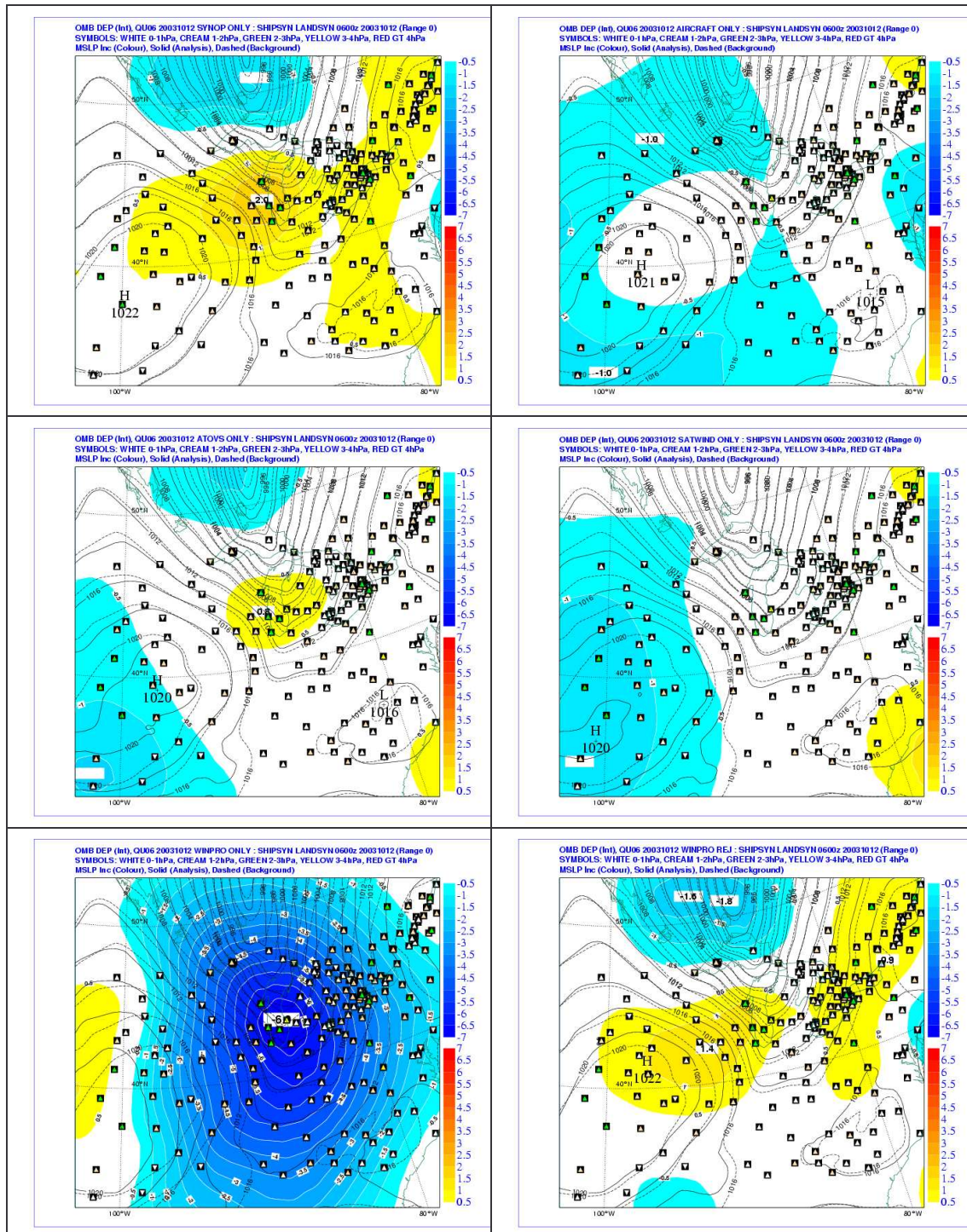


Figure 10 MSLP Analysis increments and background departure plots for QU06 12th October Re-runs. Top left: SYNOP only. Top right: AIRCRAFT only. Middle left: ATOVS only. Middle right: SATWIND only. Bottom left: Wind Profiler only. Bottom right: Wind Profiler Rejet.

Analysis increment contribution analysis as discussed in Section 4 was performed for each of the single-observation type re-runs. In the wind profiler-only rerun, the large northerly wind increments at 850hPa were reproduced to the SW of the Great Lakes (and in fact had other significant effects further east). In all other reruns, including the wind profiler reject rerun, these analysis increments were missing, confirming further the role of the wind profilers in the generation of these abnormal wind increments.

6 Wind Profiler Data

Wind profilers in the central United States are arranged in a network of 30 instruments centred around ~37N 98W (Fig 11). These profilers are designed to measure vertical profiles of horizontal wind speed and direction throughout the depth of the troposphere by the use of relatively long wavelength radar. They operate by detecting fluctuations in the atmospheric density caused by turbulent mixing of air with different moisture and temperature content, with the detected fluctuations being used as a tracer to measure the mean wind speed at that height.

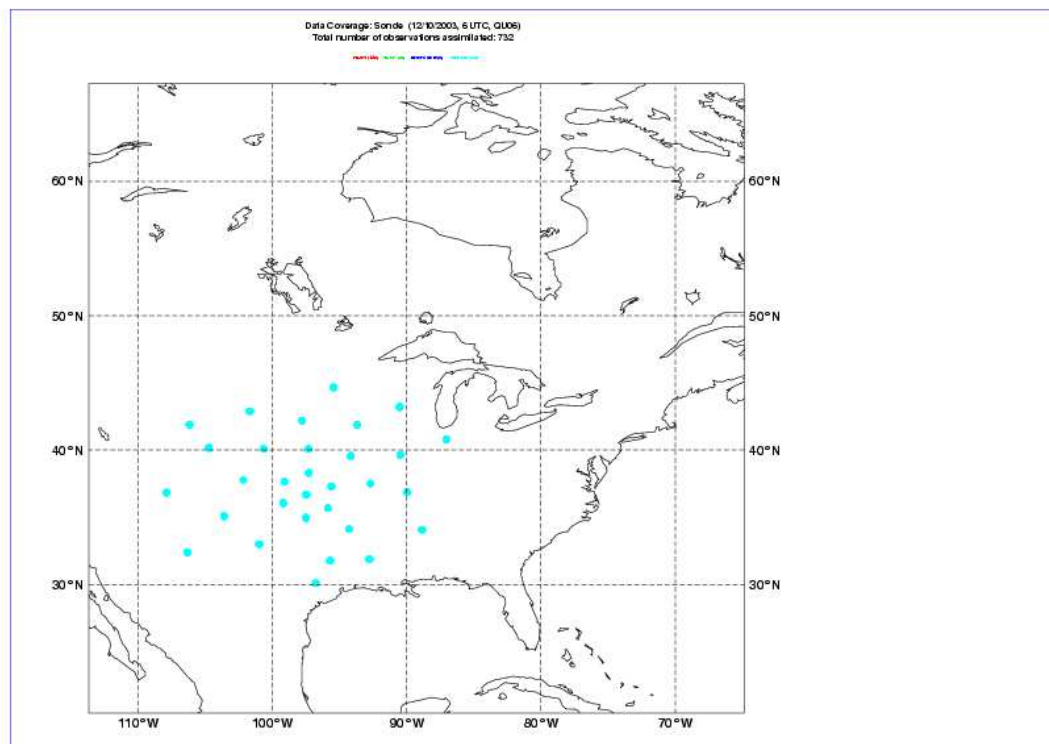


Figure 11 The wind profiler network in the USA.

In order to assess the quality of the wind profiler data, observation-background (O-B) wind speed and direction differences on various model levels were calculated for each of the wind profilers in the network. The period for the timeseries was chosen to give a good representation of the observation and background consensus over a few days and therefore to

reflect the performance of the profiler under different meteorological conditions.

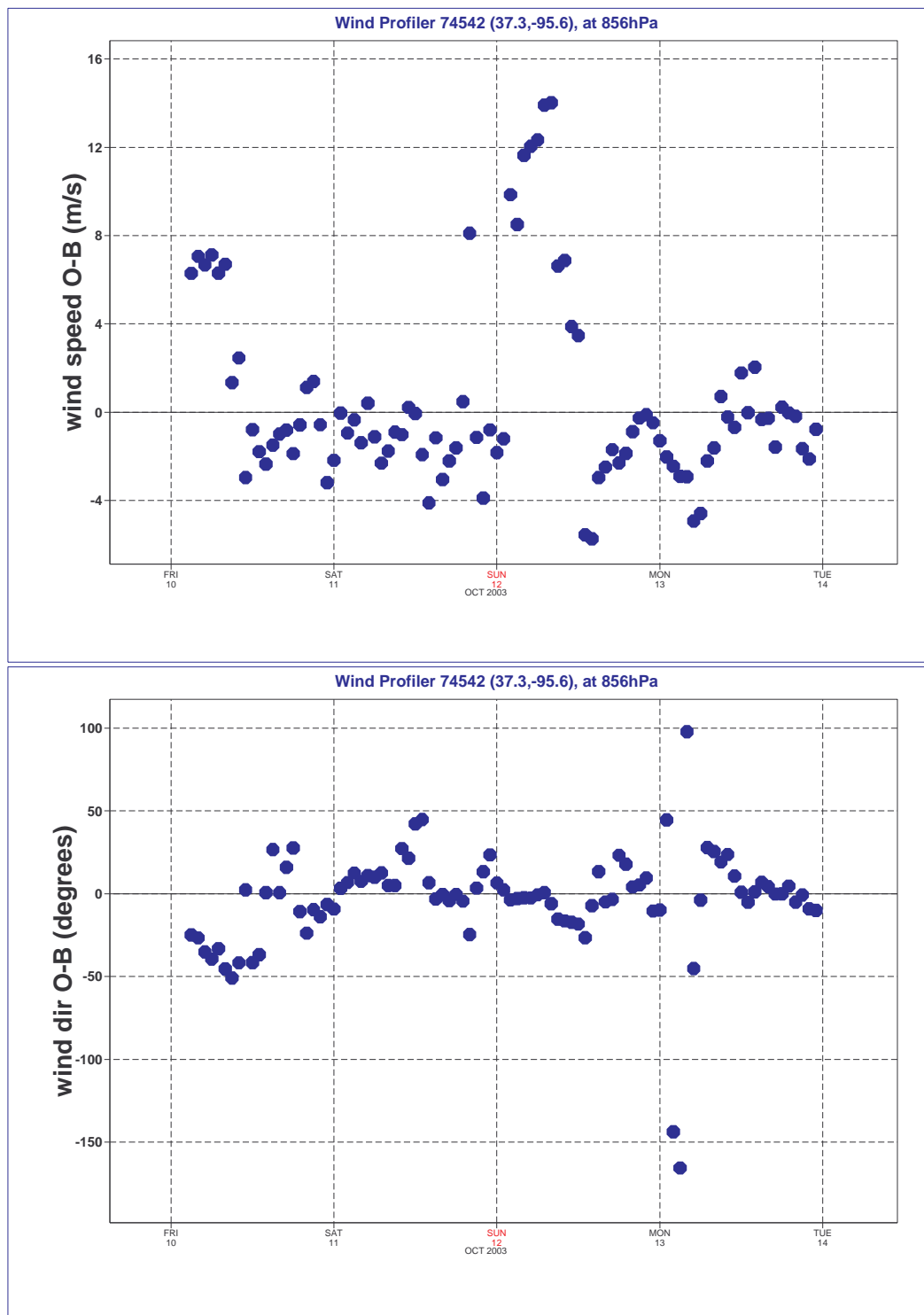


Figure 12 Observation – Background timeseries plot for wind profiler 74542, 10th-14th October 2003.

It was found that the agreement between model and observations was relatively good at upper model levels, but that there were instances of significant poor consensus at lower levels. Fig 12 shows the model level 8

(~850hPa) O-B plot for wind profiler 74542 which is situated at 37N 95W (just to the NE of the central wind profiler in the network). The timeseries shows that for the majority of the time, the observed wind speed and the background are in relative agreement (within ~ 4m/s). However, there are two instances in which the departure of the observations from the model is significantly more: the first during the 10th October, and then again during the morning of the 12th October. The latter departure shows a departure of significant magnitude of upto 14m/s, and corresponds to the assimilation time of the QU06 run under study.

Departure characteristics of this type could be indicative of a faulty wind profiler, but the magnitude of the departure is such that it should have been rejected as a result of the background check, and it is known from analysis of the quality control flags that this data was accepted. In this case it was found that ~10 wind profilers clustered to the E of 98W all exhibited the same effect. This would explain why the data was accepted into the model because the neighbouring wind profilers would have buddy-checked each other, thus overriding any rejection from the background-check stage. This would suggest that (1) the model background was in error or (2) that all the wind profiler data was corrupt in the same way. As it is known from the analysis discussed above that the background for the QU06 run verified well, then this suggests that a cluster of wind profilers covering a large area (~5 degrees longitude and ~6 degrees latitude) were all corrupt for the QU06 run.

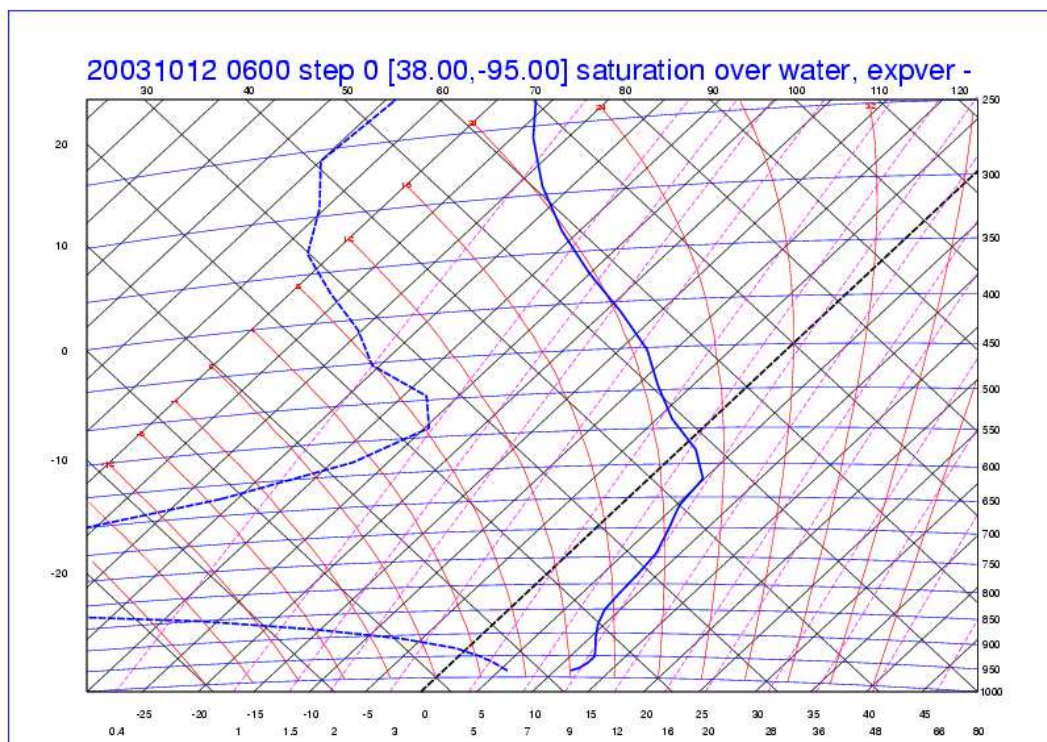


Figure 13 Model tephigram for the Control Rerun, taken at 38N 95W.

To investigate this further, a model sounding (from the control run) within the region of wind profilers under investigation was plotted and is shown in Fig 13. The sounding shows a deep and very dry layer of the troposphere upto

~550hPa. This was compared with a sounding taken from the run in which the wind profiler data was rejected (not shown), but no significant difference between the two profiles was observed. However within the lower depth of the control run, corresponding to the lower half of the dry air, wind speeds ~40kn were observed (not shown). This was in contrast to the wind profiler-rejected run in which wind speeds ~25-30Kn were identified. This core of higher winds in the control run, and the absence in the wind profiler-rejected run can therefore be directly attributed to the northerly wind analysis increments at this height and location (Fig 8) that were introduced into the analysis by the wind profiler data.

The implications of this dry depth of troposphere on the performance of the wind profilers was investigated. It was found that a known problem exists with American wind profiler data in its contamination by migrating birds (John Nash, private communication). Because wind profilers are designed to measure weak signals, they operate by averaging the radar signal over a period of ~1 minute. Even a single bird flying through the radar beam will then result in a reading of the wind speed equal to the velocity of the bird, because it is much greater than the 1 minute averaged wind speed reading. 'Hourly consensus averaging' algorithms applied to the data remove these spurious readings so that for random birds flying through the beam the data are not corrupted. However problems occur when multiple birds consistently fly through the radar beam in the same direction so that the bird contamination proportion of the signal is significantly increased. The result is an erroneous wind speed observation of 10-14m/s. Such conditions occur within the United States during the migratory seasons in which millions of Passerines (the family of birds encompassing over ~50% of the world's bird species, and loosely being regarded as all song-birds) migrate south in autumn and north in spring.

Bird contamination of the wind profiler data fits very well with the evidence:

- The case is within the autumn migratory season of the United States.
- A trough has just passed through the area thereby veering the wind to a north/north-westerly and allowing the birds to pick up a strong tail wind.
- The birds migrate on dry clear nights; conditions shown by the model profile.
- The increments occur from wind profiler data and
- The increments are northerly (due to the autumn migration) and are ~10-14m/s.

Sophisticated algorithms have been devised to flag wind profiler data at the data source in which such bird contamination is most likely, and this is transmitted along with the observation. The flag is then intended to be used by the receiving centre as a way of rejecting the data before it is processed and goes through the normal quality control steps.

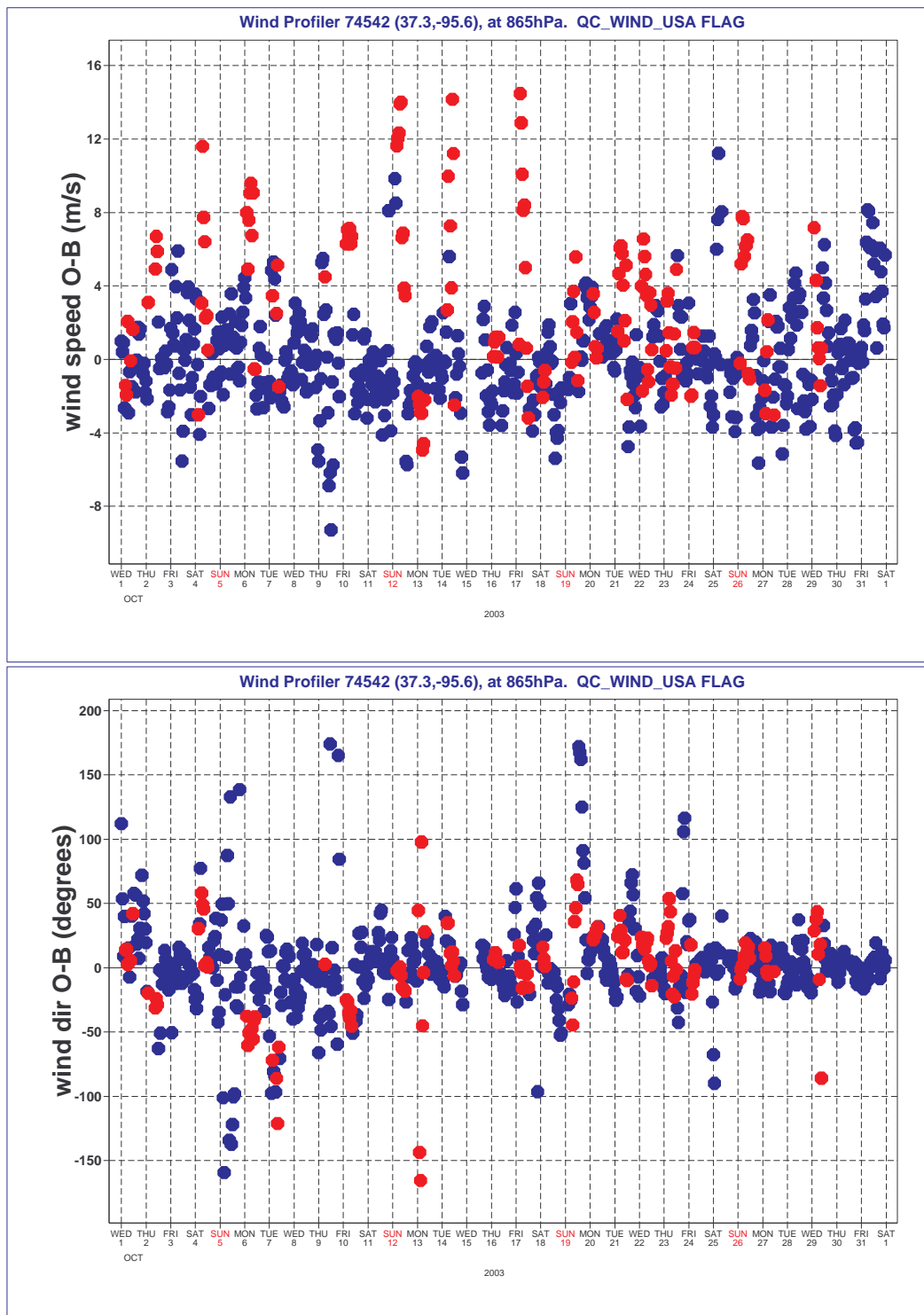


Figure 14 Observation – Background timeseries plot for wind profiler 74542, 10th-14th October 2003. The data is colour coded according to the QC Flag provided by the bird contamination algorithm. Blue: No contamination, Red: contaminated. The QU06 12th data is flagged as being contaminated by migrating birds.

Fig 14 shows an O-B timeseries plot for Wind Profiler 74542 in which the time period has been expanded to cover the month of October 2003. The data has been colour coded so that instances in which the US algorithm flagging

migrating birds has been plotted in red; non-contaminated data according to the algorithm is plotted in blue. The timeseries shows that are 6 occurrences in which the O-B departure exceeds 10m/s, 5 of which having been flagged. Of these occurrences, the wind profiler data corresponding to the QU06 12th October run has been flagged, with two other major contaminated events occurring on the 14th and 17th October.

The algorithm is reported to successfully remove ~60% of bird contaminated wind profiler data, although to also have a rather high false alarm rate of 44%. These quantities appear to agree well with the O-B timeseries of Fig 14.

7 Re-run using the Wind Profiler QC Flags

A routine within the Met Office's Observation Processing System (OPS) was modified in order to facilitate the use the wind profiler QC flags, and a Global Model rerun was performed. The analysis increments from this run at QU06 12th were found to be very similar to the previous run in which the wind profiler data had been rejected, with positive MSLP analysis increments to the SW of the Great Lakes. Fig 15 shows the background departure diagram for the verification time of the poor forecast (QU12 12th October) in the rerun using the QC flags, and this should be compared with that of the control run in Fig 6.

The degree of success of the new run may be assessed in three ways:

- The size of the analysis increments over the Great Lakes have been reduced from 4.6hPa to 2.7hPa (a 42% decrease). This may be taken as a measure of the T+6 forecast error at 12z because it is the assimilation's best fit to the observations. Without the departure information discussed above, this should be done cautiously because as illustrated by this case study corrupt data being incorporated into the assimilation would produce an incorrect analysis to compare the background with.
- The departures of the observations from the background show small departures across a very wide area. The number of observations with departures in excess of 4hPa (red symbols) has been reduced from 21 to 3 stations in the current run. Further south also the departures show a very good fit between background and observations with most stations being within 1hPa of the model – this may be compared to the control run in which many stations in this area were ~2-3hPa away from the background.
- The departures of the observations from the analysis are much smaller in the new run. This is partly because there are other wind profilers at 12z that have been flagged and hence excluded from the run, but also because assimilation has been able to achieve a better fit to the observations given its improved background.

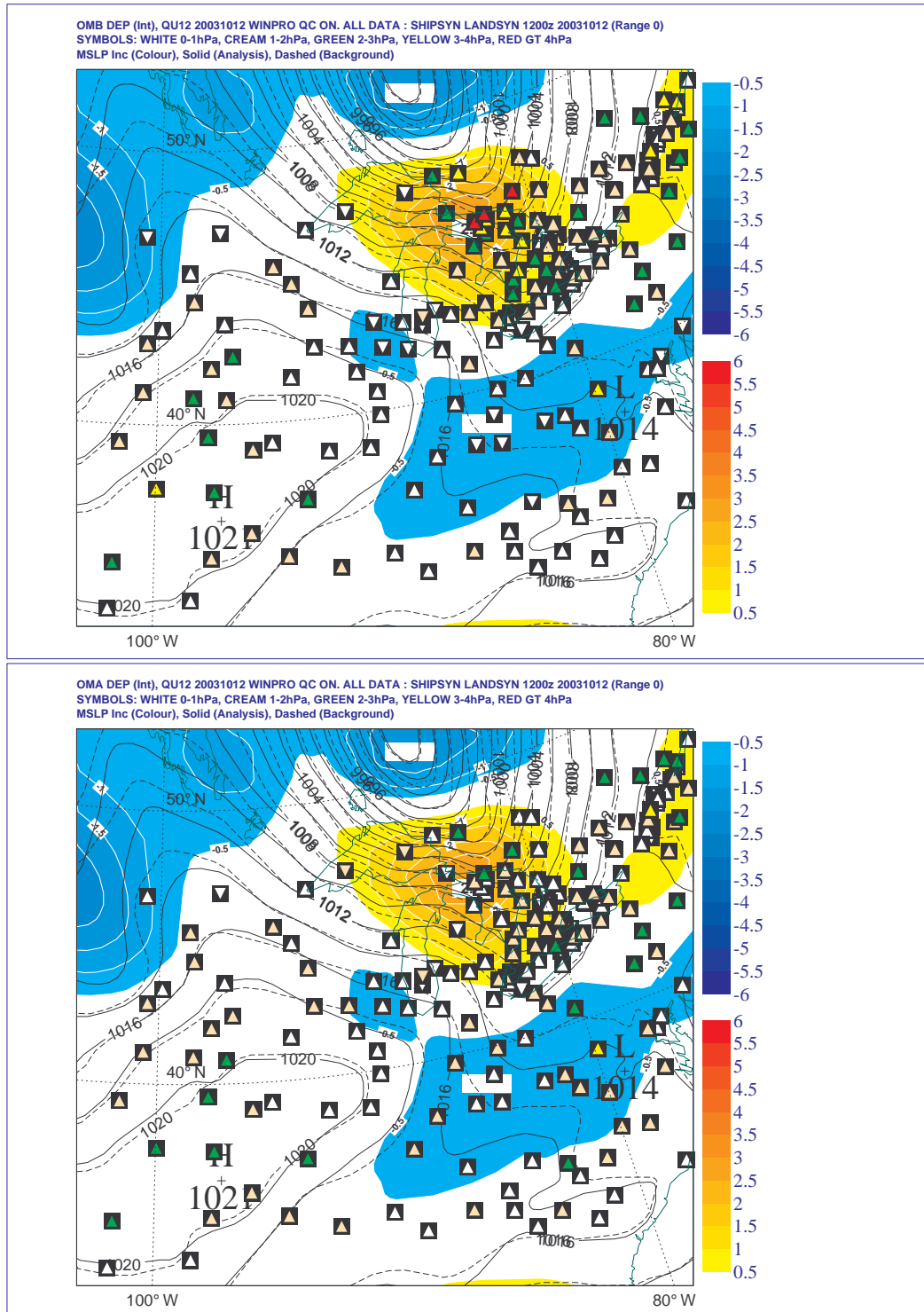


Figure 15 MSLP departures compared with MSLP analysis increments and MSLP background and analysis fields for the QU12 12th October run with UseWindProfQCFlags=TRUE. Triangles show departures from (top) the background and (bottom) the analysis, with colour coding to represent the magnitude. The sign of the departure is represented by an upward or downward facing arrow depending on if the departure is positive or negative. The figure should be compared with that for the control run, Fig 6.

Analysis increments for this run show an estimated ~90% of the 850hPa northerly wind increments removed over central USA, confirming the function

of the algorithm in removing the corrupt data and also the critical role of the wind increments in the forecast error.

8 Summary and Conclusions

A T+6 Global Model forecast verified unusually poorly over the Great Lakes on the 12th October 2003, with MSLP errors over a large area in excess of 4hPa. Investigations have been successful in tracing the error to the contamination of wind profiler data by migrating birds. This data was successful in passing through the normal quality control criteria because the wind profiler data was affected over a large area and independent stations in the wind profiler network passed the buddy checking routines, thereby overriding any background check failings.

Quality control flags are assigned to the data at source and calculated by an algorithm based on factors such as time of year, time of day, wind direction etc. The OPS has been modified in order to facilitate the use these control flags. Reruns with this facility activated have proven to eliminate the corrupt data and show a substantially improved forecast.

After further verification of the effect of the routine, it will be activated in the OPS and undergo trial as part of Parallel Suite 8. Providing no problems are encountered the routine will become operational on October 12th 2005 and will prevent ~60% contaminated US wind profiler data from entering the Global Model.

Because of the complexity of modern forecasting systems, case studies such as that documented in this report require extensive time and effort to bring the study to conclusion – and even then there is no guarantee of the discovery of an identifiable error. Nevertheless, this case illustrates the importance of carrying out routine/regular investigations into the causes of forecast errors, as the assimilation of this corrupt form of data had gone unnoticed for several years. The techniques used throughout this work have been developed as part of a routine forecast monitoring system, and will continue to be used to investigate and diagnose model errors in the future.

9 References.

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